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Papers

Evaluation of risks of foot-and-mouth disease in Scotland to assist with decision making during the 2007 outbreak in the UK

V. V. Volkova, P. R. Bessell, M. E. J. Woolhouse, N. J. Savill

An outbreak of foot-and-mouth disease (FMD) occurred in Surrey on August 3, 2007. A Great Britain-wide ban on livestock movements was implemented immediately. This coincided with the start of seasonal sheep movements off the hills in Scotland; the majority of these animals are sold via markets. The ban therefore posed severe economic and animal-welfare hardships if it was to last through September and beyond. The Scottish Government commissioned an analysis to assess the risk of re-opening markets given the uncertainty about whether FMD had entered Scotland. Tracing of livestock moved from within the risk zone in England between July 16 and August 3 identified contact chains to 12 Scottish premises; veterinary field inspections found a further three unrecorded movements. No signs of infection were found on these holdings. Under the conservative assumption that a single unknown Scottish holding was infected with FMD, an estimate of the time-dependent probability of Scotland being FMD free given no detection was made. Analyses indicated that if FMD was not detected by early to mid-September then it was highly probable that Scotland was FMD free. Risk maps were produced to visualise the potential spread of FMD across Scotland if it was to spread either locally or via market sales.

AN outbreak of foot-and-mouth disease (FMD) in Surrey on August 3, 2007, which occurred due to the virus escaping from a research facility (Spratt 2007), led to an immediate Great Britain-wide ban on livestock movements. This posed economic and animal-welfare hardships for the Scottish livestock industries as sheep trade in Scotland peaks annually from mid-August through September (Volkova and others 2008). Sheep must be moved off the hills at this time to avoid starvation and hypothermia.

On August 13, 2007, the Scottish Government commissioned an assessment of the relative risk of resuming sheep sales via markets. Their concern was the risk that FMD might be present in Scotland, and would spread if livestock movements resume. During the preceding outbreak of FMD in Great Britain in 2001, the virus disseminated with livestock being moved via markets or to abattoirs, or was carried on the vehicles and personnel involved in the movements, followed by local (within 3 km) spread via multiple conveyors (Gibbens and others 2001). An

assessment of freedom of a territory from a reportable livestock disease normally involves a purposively designed survey of the host population. This option was not available to us for the evaluation of FMD in Scotland in 2007 due to the continued economical and animal-welfare pressures with continuation of the livestock movement ban. We therefore followed an alternative approach and agreed with the Scottish Government that addressing the following four questions would provide the evidence necessary to assist with their decision-making.

Question 1: Identify direct livestock movements between July 16 and August 3 from a 20-km risk zone centred around the two FMD-infected farms and two dangerous contact premises in Surrey into Scotland, and into the English counties bordering Scotland. The latter was important because of the potential for local disease spread across the Scottish border.

Question 2: Perform contact tracing of livestock moved into Scotland that may have been exposed to the livestock originating from within the risk zone between July 16 and August 3.

Question 3: Estimate the time-dependent probability that Scotland was free from FMD given that no FMD was detected.

Question 4: Assess the month-by-month magnitude of contact between Scottish markets and farms via sheep movements using the movement records for 2006.

Two further outputs were considered useful to understand the potential for dissemination of FMD in Scotland and to prioritise the response on the ground should the disease be detected.

Question 5: visualising potential dissemination of FMD via market sales of sheep.

Question 6: project potential local-spread of FMD, if any of the holdings identified in questions 1 and 2 above were infected.

Materials and methods Livestock movement records

Animal movement records were extracted from three British livestock movement databases: the Scottish Animal Movement System

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(SAMS) and the Animal Movement Licensing System (AMLS) for sheep, pig, goat and farmed deer batch movements; and the Cattle Tracing System of the British Cattle Movement Service (CTS) for individual cattle movements. The SAMS extracts were supplied by the Scottish Government, and those from AMLS and CTS by the National Emergency Epidemiology Group of the Department for Environment, Food and Rural Affairs (DEFRA).

Movement record analysis for contact tracing (questions 1 and 2)

The following computer algorithm was implemented to contact-trace animals from within the 20-km risk zone in England into Scotland. The three database-extracts were scanned for any movements between July 16 and August 3 from that zone to secondary holdings. Any movements into Scotland were recorded. The databases were scanned a second time for any movement from a secondary holding to a tertiary holding that occurred on or after the date of the primary to secondary movement. Again, any movements into Scotland were recorded. This process was repeated until no further movements were identified. Only movements of animals between holdings, but not those to abattoirs, were considered.

Time-to-detection and probability of disease freedom (question 3)

The worst-case scenario was considered to be a case of a single unknown Scottish holding harbouring FMD by the time of the implementation of the livestock movement ban on midnight of August 3 (having more than one infected holding would increase the chance for detection). Detection of FMD on such a holding was assumed to occur if the animals were moved under licence to abattoir or on welfare grounds; moved within the same business (8-km business zone); or if they became symptomatic after an incubation period. In those three movement-associated detection situations, the animals would be examined for signs of FMD. We therefore assumed that FMD would be detected in the movement-associated examination of animals moving off the infected holding. Incubation period was defined as the maximum time from effective exposure to FMD virus to the clinical manifestation of disease in the animals, with the exposure occurring at the time of the implementation of the movement ban. Worst-case scenario incubation periods of two and three weeks on a holding with no movement-associated inspection of animals were considered for a holding with cattle or pigs, and two, four and six weeks for a sheep-only holding.

Holdings with individual livestock species would go through the three movement-associated detection situations at different rates; this was explicitly specified in the analysis as follows: the numbers of holdings with each livestock species were obtained from publicly available results of the agricultural census of Scotland in June 2006, the Scottish Government supplied the numbers of Scottish sheep, cattle and pig holdings sending animals to Scottish abattoirs under licence weekly after August 8, when such moves started and they also provided the number of holdings issued with licences for animal movements on welfare grounds by August 21. In terms of movements within the same business (8-km business zone), the Scottish Government estimated that from August 20 to 25 there were 1200 such movements on sheep-only holdings and 1200 such movements on holdings with other livestock. Thereafter, roughly 10 per cent of all livestock holdings moved animals within 8-km business zones per week. The 15 holdings identified by contact tracing (see above) were modelled explicitly using the dates of the veterinary inspections on these holdings. These holdings were classified as a sheep-only holding if the traced in-movement was sheep, and as a cattle holding if the traced in-movement was cattle.

The time-to-detection analysis was performed using PROC LIFETEST procedure in SAS® 9.1 software for Windows (SAS Institute Inc., Cary, NC, USA). The product-limit estimate (also called Kaplan-Meier estimate, non-parametric maximum likelihood estimate) of the survival function was used. The survival function evaluated the chances for a farm in Scotland exposed to FMD by the time of implementation of the movement ban to remain undetected beyond a given date. In other words, we estimated the probability of not having detected FMD in Scotland by a certain date as the proportion of total

holdings that had not yet been examined for signs of disease and had not yet manifested the signs after an incubation period.

The posterior probability that Scotland is infected given that no FMD has been detected by a certain day is calculated using Bayes' theorem, where I is the event that a single holding is infected ('Scotland is infected'), I^c is the event that no holding is infected ('Scotland is FMD free'), and U_t is the event that FMD has not been detected by day t . Then the Odds form of Bayes' theorem states (Lindley 2006):

$$\text{Odds}(I|U_t) = \text{Odds}(I) \times \frac{\Pr(U_t|I)}{\Pr(U_t|I^c)} \quad (1)$$

where $\text{Odds}(I)$ is our prior belief that Scotland is infected at the time of implementation of the movement ban, $\text{Odds}(I|U_t)$ is our updated belief on day t of Scotland being infected given no detection of FMD by that day. If there is no infection in Scotland then it cannot, of course, be detected, therefore $\Pr(U_t|I^c) = 1$. Therefore:

$$\text{Odds}(I|U_t) = \text{Odds}(I) \times \Pr(U_t|I) \quad (2)$$

The likelihood $\Pr(U_t|I)$, is informed by the time-to-detection analysis described above.

Potential spread via sheep market sales (questions 4 and 5)

From the SAMS records, the numbers of farms sending sheep to, and receiving sheep from, each Scottish market each month of 2006 were

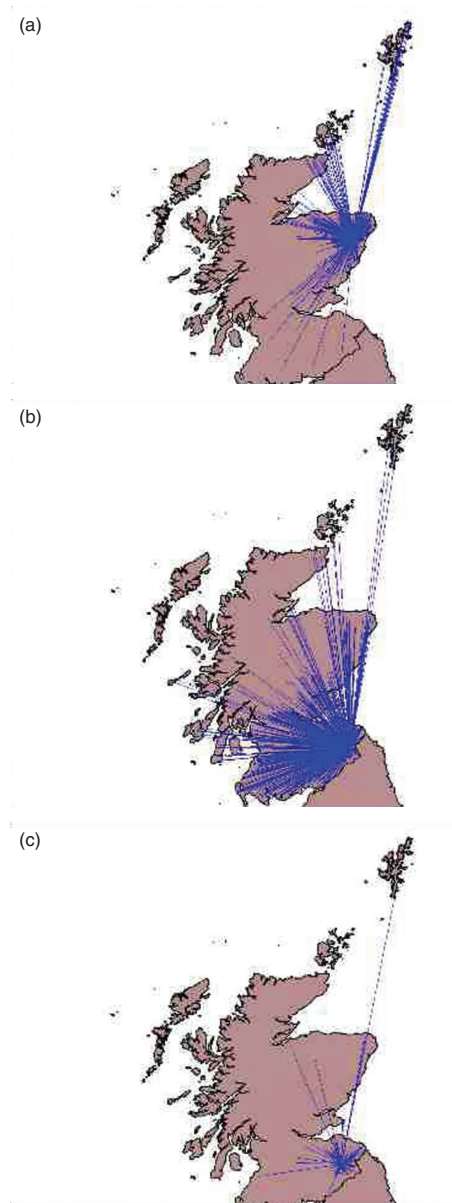


FIG 1: Distribution of sheep movements to the Scottish farms from (a) a northern market, (b) a southern market and (c) the Kelso ram sale during August and September 2006

plotted (data not shown). Potential dissemination of FMD via market sales of sheep was visualised by mapping the spatial distributions of the sheep movements to the farms from several major sales, including the Kelso ram sale, held in August and September of 2006. A small amount of error was introduced into coordinates of the receiving farms in the map in order to prevent identification of individual holdings.

Potential local-spread (question 6)

The map of the potential local-spread of FMD in Scotland was based on an a priori developed logistic regression model of holding-level susceptibility to FMD infection via local-spread parameterised from the UK's FMD 2001 outbreak data (Bessell and others 2008, 2010, Bessell 2009). The model included four sets of predictors for a holding: the distance to a source of infection (that is, seed, defined for the 2001 epidemic as a holding infected before the national movement ban, and defined here as a holding implicated by the contact tracing), species farmed, geographical size and the numbers of livestock in the surrounding area. The predicted probabilities of the infection for all farms in Scotland were calculated. Using these data points a raster map was derived based upon the sum of these values within 3 km of each cell in a 100 x 100 m² cell size grid. The map was produced with ArcView® 9.2 (ESRI, Redlands, CA, USA).

Results

Contact tracing

Contact tracing did not identify any direct movements of livestock onto Scottish holdings from the 20-km risk zone in England between July 16 and August 3. Twelve holdings in Scotland were identified as being at risk of FMD due to potential indirect contacts. In particular, six sheep were moved on July 21 from a single holding within the risk zone to a Welsh showground. Five days later, sheep were moved from this showground, either directly or indirectly via a market, onto five holdings in Scotland. Whether they were the same sheep was impossible to tell because sheep movements are recorded in batches in the AMLS and SAMS databases.

For cattle movement, four potential contact chains were identified. They originated in the risk zone on July 16 and 20 and resulted in 110 animals moving onto six holdings in Scotland on August 1, and one animal moving onto another holding on August 2. None of these cattle were from the risk zone; this could be determined because CTS records the movements of individual cattle identified by their passport numbers. No potential contact chains into Scotland via movements of pigs, goats or farm deer were identified.

No signs of infection were found on these 12 Scottish holdings by veterinary field inspections. While carrying out their inspections, the veterinarians identified a further three unrecorded movements to other holdings. These holdings were also inspected with no signs of infection.

Contact tracing into English counties bordering Scotland identified 35 holdings potentially at risk. No field inspections were carried out on these holdings.

Potential spread via sheep market sales

The number of farms receiving sheep from a single Scottish market during a month in 2006 ranged from one to over 800. The total number of sales to the farms was at its highest from August to November. Because of these numerous contacts between the markets and farms, opening Scottish markets for sheep trade during this period poses a relatively high risk of spreading FMD, if present, to multiple farms.

The spatial distributions of the sheep movements to Scottish farms from a northern market, a southern market and the Kelso ram sale during August and September 2006 are shown in Fig 1. From 180 to 850 farms received sheep from each of these markets. The median distance the sheep travelled was 43 km (mean=72.5 km), however, the distance travelled varied from 1 to 558 km, with an interquartile range of 78 km. Clearly, opening Scottish markets for trade during August and September poses a high risk of wide geographical spread of FMD if present in sheep in Scotland.

Potential local-spread

Assuming that 14 of the 15 at-risk holdings in Scotland (coordinates were not available for the other one), and the 35 contact-traced English

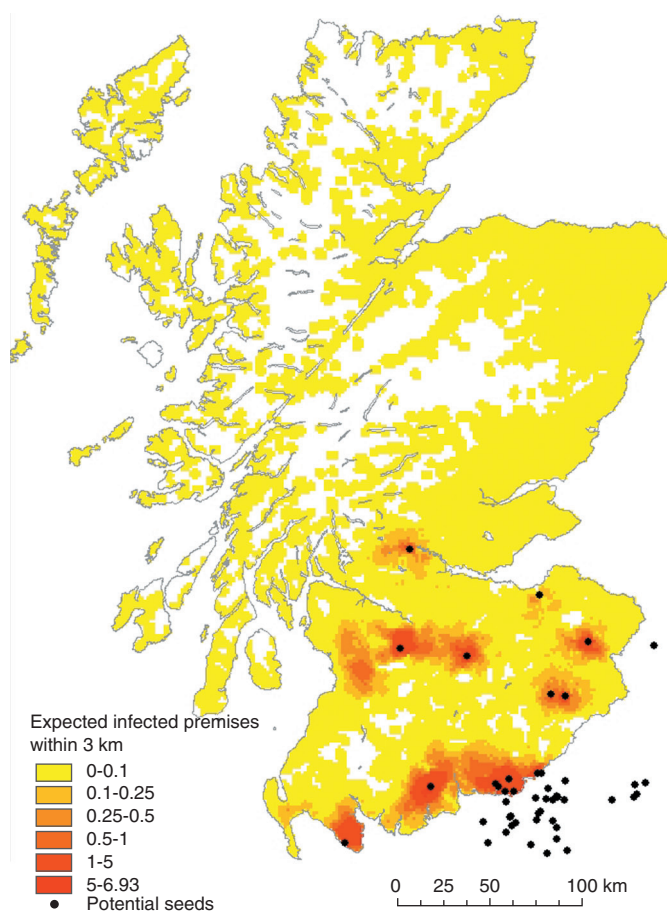


FIG 2: Risk map of potential foot-and-mouth disease local-spread in Scotland if 14 of 15 at-risk holdings in Scotland and 35 such holdings in North England were infected

border county holdings are all infected with FMD, Fig 2 shows the colour-coded representation of the expected number of holdings within 3 km of each of these holdings that would become infected via local-spread given a similar outbreak progression, disease control strategies, and virus characteristics as in 2001.

Time-to-detection and probability of disease freedom

The analysis indicates that the probability for a single FMD-infected livestock holding in Scotland remaining undetected dropped from 100 per cent on August 6, to lower than 50 per cent by August 21 under all of the scenarios of incubation periods (solid black lines, Fig 3). The probability dropped below 10 per cent in all scenarios by the second week of September. The duration of the incubation period on sheep-only holdings had a marked effect on how rapidly the probability of FMD not being detected declined.

Discussion

Contact tracing of livestock, based on record-collating systems such as CTS, AMLS and SAMS, was very useful for the early prioritisation of surveillance effort in Scotland following the detection of FMD in Surrey. This was because it was possible to direct the veterinary inspections only on the holdings at risk. However, the AMLS and SAMS databases record livestock movements as a batch, not at an individual level. This limited the ability to distinguish the movements of sheep from the risk zone into Scotland from the potential-exposure contact chains. Development of AMLS and SAMS systems to record movements of individual animals, based on animal passports (similarly to that done in CTS for cattle), will improve the resolution of surveillance based on these systems, thereby allowing more efficient deployment of resources during an infectious disease outbreak. We also observed that delayed reporting of livestock movements by animal keepers, long processing times required for the resulting large datasets, and unknown frequency of undisclosed movements limited the utility of the records collated by the British livestock movement databases.

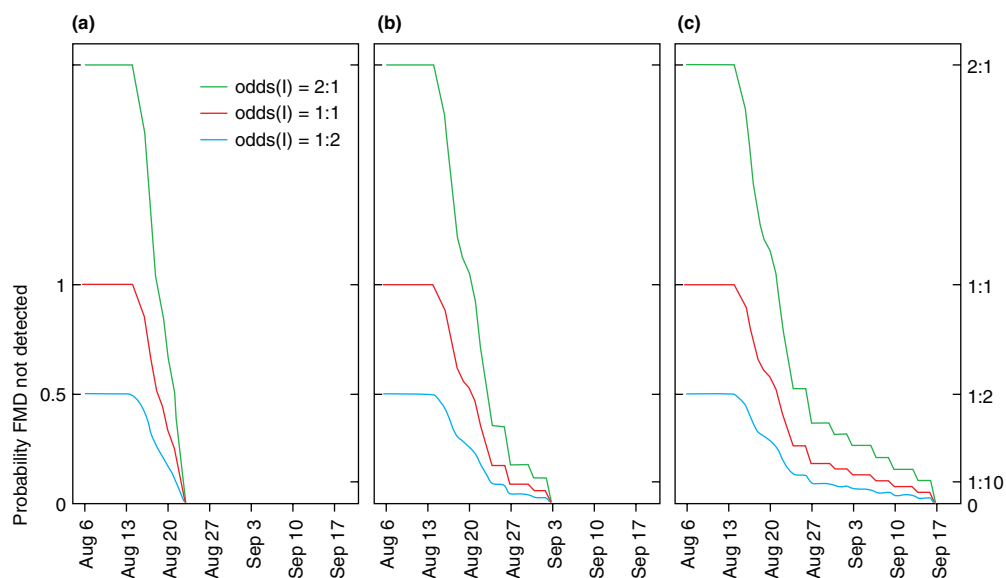


FIG 3: Probability of not detecting foot and mouth disease (FMD) over time given the worst-case scenario of a single infected holding somewhere in Scotland (black solid lines). Posterior belief, in terms of odds, that there is an infected holding in Scotland given no detection over time for prior odds of 1:2 (dotted red lines), 1:1 (solid black lines) and 2:1 (dashed green lines) of FMD present in Scotland at the time of the implementation of the movement ban. (a) Incubation period of two weeks for all holding types. (b) Incubation period of three weeks for cattle and mixed holdings and four weeks for sheep-only holdings. (c) Incubation period of three weeks for cattle and mixed holdings and six weeks for sheep-only holdings.

The local-spread risk map outlined the regions in immediate need of follow-up measures should FMD be detected on an at-risk holding, and was prepared to stand-by. The ability to forecast the risks is conditional on the availability of the modelling tools, the up-to-date data on livestock demographics to feed into the models, and qualified professionals able to timely deliver the evidence to decision makers.

Infection of a sheep-only holding appears to pose the greatest risk of FMD remaining undetected in Scotland. This, however, depends on the length of incubation period, and on how often and how thoroughly the animals are inspected. For a given incubation period, the time-to-detection may be shorter during the periods of the year when a larger fraction of farms are moving sheep to abattoirs, off the hills or otherwise within business zones. At these times, not only the risk of spread but also the likelihood of disease detection is at its highest.

Our belief in whether FMD is in Scotland given that it has not been detected by a certain date depends on our prior belief (informed by other sources of information and our knowledge of FMD epidemiology) that FMD got into Scotland before the Great Britain-wide ban on livestock movement. Three scenarios are shown in Fig 3 using odds as a measure of belief. As Equation 2 demonstrates, our posterior odds on FMD being in Scotland given that it has not been detected by a certain date is just the probability of not detecting FMD by that date scaled by our prior odds. As more evidence accumulates that FMD is not in Scotland (that is, as time passes and it is not detected) our belief that FMD is in Scotland falls. How quickly that falls depends on our prior odds. The more we believe FMD got into Scotland before the movement ban, the more evidence we need to convince ourselves that Scotland is FMD free. Or, equivalently, on a certain day postmovement ban, we are more likely to believe that Scotland is FMD free than someone else if our belief that FMD got into Scotland pre-movement ban was lower than theirs.

Time-to-detection of FMD was analysed assuming that any livestock moved (to slaughter, for welfare reasons or within the business) was inspected for signs of FMD, and that the inspection would detect FMD in at least one animal if the holding was infected. Although the former may have been a reasonable assumption due to the alert state of the industry, the latter, though, may have been an overestimate because detecting signs of FMD in sheep is difficult. However, we did consider

the worst-case scenario of a single infected holding. If FMD had been introduced onto, or spread, to more than one holding pre- or postmovement ban this would increase the chances for detection. Therefore the quantitative results of the time-to-detection analysis should not be interpreted literally. Indeed, they were not. Instead, they were used to aid in decision-making together with the other evidence available.

Understanding the probability of undetected FMD in Scotland, and how this was influenced by a priori personal beliefs, helped decision makers to judge the degree of risk. This was, of course, considered against the economic and animal-welfare consequences of prolonging the movement ban. The results of this evaluation of risks were used by the Scottish Government for negotiating with national stakeholders and the European Commission. Livestock markets in Scotland were re-opened on

August 23, 2007 (Scudamore and Ross 2008).

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